Optical switching applications of ZnSe/MgF2 photonic band gap structures based on thermal nonlinearities

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We designed and realized a ZnSe/MgF_2 multilayer structure deposited on silicon heaters, in order to obtain the modulation of its optical reflectance near the band edge. An electrically induced temperature increase can be electrically applied to the resulting device and, therefore, a change in the refractive index of the layers is produced. As a result the band edge is red-shifted and the absolute signal is decreased. The particular design of the substrate, allow the application of a temperature increase to the multilayer stack by means of an applied current to the underlying heater. The proposed structure works in reflectance and allows the optical switching of the incident beam when the heating is activated.

Specifically, we fabricated a one-dimensional photonic band gap structure based on ZnSe [1,2]. The multilayer stack was deposited by thermal evaporation over the optical-active area of the silicon wafers. The layers stack is composed by 8 periods of ZnSe/MgF_2. From the optical point of view, the reflectance spectrum presents a band-edge at 628 nm, i.e. accessible to a low power He-Ne laser. The reflectance spectra have been measured under different applied voltage and a maximum shift of 7 nanometers has been observed, corresponding to a signal reduction of nearly 40% of initial value.

As a conclusion, we show experimentally that the combined use of a high thermal nonlinearity in a multilayer stack included in a electrically heated structure, result in strong variation of the reflected light intensity. This structure offers large potentiality for optical switching applications

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Controlling coherence in single photon microcavity emitters

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The exploitation of quantum physics in information processing or communication has created a demand for compact sources capable of delivering single photons that can display quantum correlations by being indistinguishable or entangled. We are developing such sources, based on single self-assembled semiconductor quantum dots. A major difficulty in obtaining indistinguishable or entangled photons stems from the fact that, during photon emission, the de-phasing of the emitting state produces random phase interruptions which destroy photon indistinguishability and entanglement. In order to restore these manifestations of quantum coherence, it is necessary to engineer photon emission through the exploitation of Cavity Quantum ElectroDynamics effects that occur when placing a quantum dot in a microcavity. By making photon emission happen faster than dephasing, coherent effects can be restored.

To this end, we develop structures in which the quantum dot is embedded in a semiconductor membrane that is etched to form a photonic crystal, with cavities formed by the introduction of periodicity defects. In this talk, we shall discuss the physical considerations for the restoration of photon indistinguishability and entanglement in the emission of a quantum dot, the constraints on cavity design, and the technological issues associated with fabrication. We shall present several devices we fabricated as solutions to these problems, and in particular we shall present microcavities capable of restoring photon indistinguishability and shall discuss our work towards cavities capable of restoring entanglement in the biexcitonexciton photon cascade.

Spectral self-similarity in fractal one-dimensional photonic structures

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Fractal one-dimensional (1D) photonic structures exhibit scalability in transmission spectra, which results from its geometrical self-similarity (SS) [1]. Here we report that besides scalability, optical spectra of 1D fractal structures possess self-similar (or fractal) properties. Unlike in quasiperiodic structures where transmission peak frequencies form a fractal Cantor set [2], SS in fractal structures is present in the shape of transmission spectra envelopes, i.e., in the relative depth of dips between transmission peaks. To observe SS and scalability appearance, one needs to apply a power transformation of transmittance magnitudes in addition to the frequency scaling (Fig.1). The scaling factor and the value of power are both related to the geometrical parameters of the structure in question. Our conclusions are illustrated numerically by some examples.

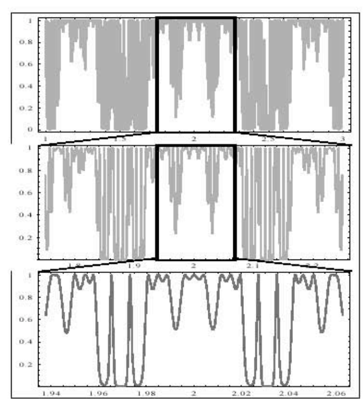

Fig. 1. Transmission spectrum $T(\omega)$ of (4,{1,2},5) fractal structure (see [1] for notation), the central area repeatedly scaled in frequency by 4 and T raised to 7th power

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Photonic crystal microcavities for spontaneous emission control

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The fabrication of semiconductor resonant cavities, which trap light within a finite volume to enhance the interaction between the electromagnetic field and a single quantum dot embedded in the cavity, is one of the current challenges in photonics. It would make possible exciting new applications in quantum optics ranging from efficient single photon sources to single dot lasers. We are developing such sources, based on single self-assembled semiconductor quantum dots embedded in two-dimensional photonic crystals cavities etched in a GaAs membrane suspended in air or lying on an AlOx layer. In these structures, the 2D photonic crystal lattice provides in-plane confinement while index guiding is used to achieve confinement in the vertical direction.

In this talk, we shall discuss the technological issues associated with fabrication of such resonators. The photonic crystal cavity is fabricated by etching a triangular lattice of air holes in a 180 nm-thick GaAs membrane. The lattice constant of the photonic crystal is about 260 nm with a hole radius around 80 nm in order to obtain H1 (one-hole-missing) cavities operating in the 900-1000nm range. These cavities are fabricated through a three-step process which makes use of electron-beam lithography, reactive ion etching and chemical etching or oxydation to form the membrane. For single-hole defect cavities, suspended in air or lying on an AlOx layer, characterization measurements will be presented using the photoluminescence of layers of self-assembled quantum dots emitting around 950 nm as probes of the cavity modes.

Characterization of nanophotonic devices and subwavelength structures

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Subwavelength structures and photonic crystal devices are attracting growing attention due to their unique capabilities to control various properties of the optical field and their great potential for monolithic integration. In spite of recent advance in micro and nanofabrication technology, the fabrication of these devices is still challenging. The performance and the functionality of the fabricated devices often deviate from the theoretical expectation. Moreover, monolithic integration of discrete devices and their interactions on the nanoscale needs to be better understood by investigating near field interactions. It is, therefore, essential to develop near field characterization tools that allow accurate measurements of the individual structures and the interaction between various components. In this paper we present several characterization approaches including near field microscopy detecting complex amplitude, far field characterization and heterodyne imaging technique. Using these methods we demonstrate CW and ultrashort pulse response for various nanophotonic components including photonic crystals, photonic crystal waveguides, ultrashort plasmon-polariton waved in nanohole arrays, and other novel nanophotonic devices.

Controlled growth of opal and inverse opal films

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A new capillary-assisted deposition method for the preparation of three dimensional opal films and opal heterostructures as well as inverse opal films has been developed. By this new method, the film thickness, the crack arrangement and distribution in the opal films can be easily controlled. Alternatingly structured lateral opal heterostructures consisting of different spheres has also been derived from this method. A special set-up, which combines a capillary tube and a capillary cell, has been exploited to utilize capillarity and to fulfill the above achievements. The capillary tube transports the suspension from a container to the capillary cell, while the capillary cell helps to assemble the spheres, forming the three dimensional colloidal crystals. The set-up defines the drying fronts, and thereby thickness and crack arrangements of the opal films. The two-capillary set-up is also useful for the infiltration of opal films with a titania precursor. After calcination, inverse titania opal films with the skeleton structure have been obtained.

Design of photonic crystal functional elements by a plane-wave-based transfer-matrix method

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Recently we have developed a plane-wave-based transfer-matrix method (PWTMM) to investigate the optical properties of photonic crystals (PCs) [1-3]. We have successfully advanced this formulation from its standard area of application to solve band structure, transmission and reflection spectra to handle Bloch-mode scattering problems [4]. We have used the method to examine coupling problem of 2D PC waveguides [4-6], 2D PC filters [4], modal coupling and conversion in multimode PC waveguides [7], and semiconductor nanowire laser arrays [8]. In this talk we will report our recent progress in using the PWTMM to design high-performance PC functional elements. In the first example, we discuss the discovery of wideband continuous tunability of high-performance PC channel-drop filters that are realized by simply changing the radius of cavity rods [9]. As the second example, we discuss the optical performance of filters made from coupling waveguide-cavity structures in a semiconductor 2D PC slab [10]. The transmission, reflection, and radiation loss spectra of guided waves through this filter are accurately determined. From this information we can find out the filter of optimum performance. In the final example, we examine a T-shape beam splitter built on a 2D PC slab. Similarly, based on the information of the transmission and radiation loss spectra, we can yield an optimal design of the beam splitter. These examples indicate that the PWTMM is an accurate, convenient, and efficient numerical tool for exploring and designing PC functional elements and integrated circuits.

[1] Z. Y. Li and L. L. Lin, *Phys. Rev. E,* **67**, 046607 (2003).
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Investigation of distortion effect for photonic crystal taper

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Photonic crystal waveguides (PCWGs) is one of the most basic structure that is created from photonic crystal by introducing a linear defect to the lattice. However, for transmission in the communication wavelength, the size of waveguide needs to be is sub-micron or nanometer scale. This poses various problems with coupling as the greatest challenge. Tapers have been integrated to provide modal conversion between light sources and PCWG. Smooth linear taper[1,2] is designed through distortion of the regular lattice structure. The distortion effect is not felt when the taper angle is very small. However, for small taper angle, the taper will need to be reasonably long for good coupling efficiency with fixed input and output width. We investigate the maximum taper angle for photonic crystal taper before the distortion effect becomes significant. Above this taper angle of 23° or taper length shorter than 9.41 μm, the transmission spectrum of the taper is unstable.

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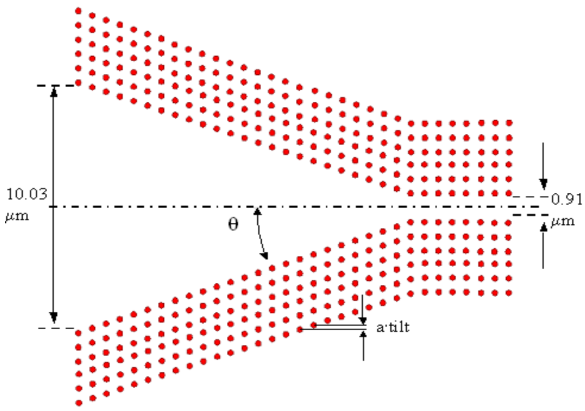

Figure 1: Smooth linear taper by distortion of crystal lattice

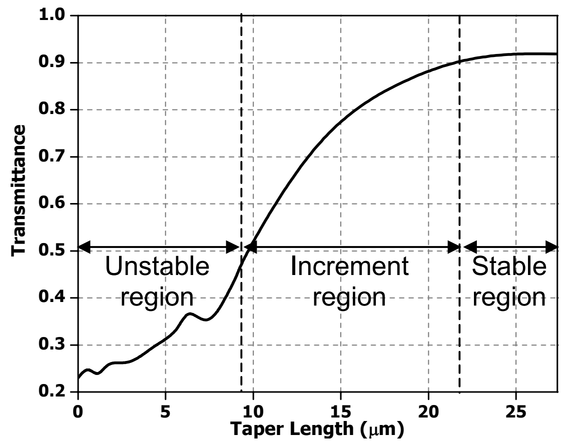

Figure 2: Unstable readings for taper angle greater than 23° or taper length shorter than 9.41 μm

Multipole physics for mode enhancement in photonic crystal taper

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Photonic crystal waveguides (PCWGs) have been a subject of much interest for guiding of light due to the presence of localized modes in the photonic bandgap. However, coupling to the photonic crystal waveguide poses a great challenge to many researchers due to it small size for applications in communication wavelength. Simple taper[1] structure has been design to be integrated with PCWG for coupling light effectively to the waveguide but have high losses due to back reflection, scattering and radiation mode coupling. Defects have been added to the taper structure to reduce these losses through mode enhancement for tapers. The physics behind the roles of defects is due to the multipole effect of the defects as a secondary oscillator source. The changes in charge distribution of the defects causes change the emission direction and angle. For this paper, the defects are tailored to change the emission directionality and angle through the change in geometry. This increases the coupling efficiency from 70% to 82% for mode conversion in simple taper.

[1] T. D. Happ, M. Kamp, and A. Forchel, Optics Letters, **26**, 1102 (2001).

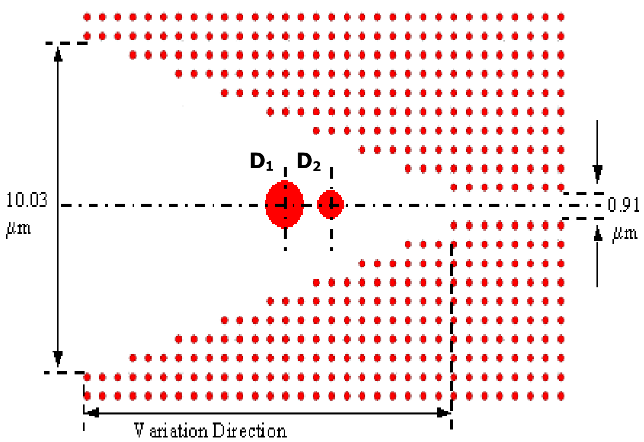
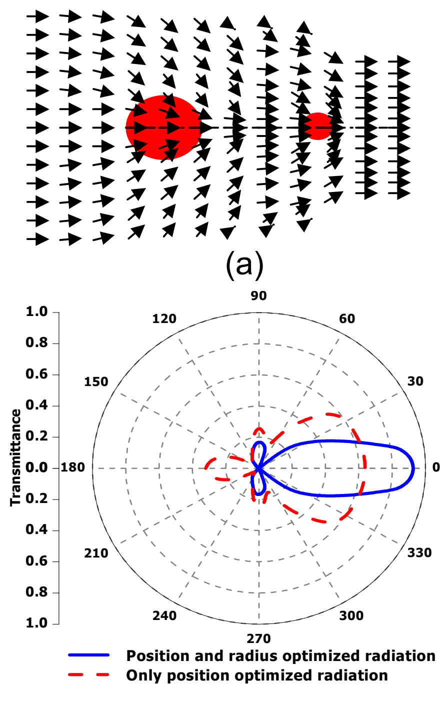


Figure 1: Schematic layout of the defects In a photonic crystal taper



(b)

Figure 2: (a) Vector field plot (b) Polar plot of the defects as a secondary oscillator source

Observation of band gaps and self-collimation for liquid surface waves propagating in periodic structures

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Waves propagating in periodic structures are strongly modulated by the introduced periodicity. As a result, multiple Bragg scatterings in periodic structures lead to complicated band structures. Between bands there may exist band gaps for waves with frequency within which propagation is absolutely forbidden. The most noticeable example is electronic band gaps in semiconductors. It has been found recently that band gaps can also exist in other kinds of waves propagating in periodic structures, e. g., electromagnetic waves in photonic crystals and sound waves in sonic crystals. The existence of band gaps renders a control of wave propagation in a desired way possible.

When propagating in periodic structures, liquid surface waves will be also modulated by the introduced periodicity. Band structures and band gaps [1,2] can also exist in liquid surface waves. As a result, many interesting phenomena found in photonic or sonic crystals can also exist in liquid surface waves. For instance, we successfully observed the superlensing effect in liquid surface waves [3]. In the present work, we will present the experimental observations in a visualized way that complete band gaps and self-collimation effect do exist in liquid surface waves when propagating over a periodically drilled bottom.

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Photonic crystal characterization using out of plane scattering

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[1]Institut de Photonique et d'Electronique Quantique, [2]Laboratory of Optoelectronics of Molecular Materials, Ecole Polytechnique Fédérale de Lausanne, CH-1015 Lausanne, Switzerland. [3]Opto+, Alcatel Research & Innovations, Route de Nozay, F-91460 Marcoussis, France. [4]Electronics Laboratory, Swiss Federal Institute of Technology, Zurich, Switzerland.

An experimental technique to investigate the optical properties of two-dimensional Photonic Crystals (PhCs) will be presented. Light that is scattered out of the propagation plane is normally viewed as an unwanted effect in PhCs as it leads to propagation losses. However, this scattered light is strongly correlated with the light propagating in the PhC and can be used to obtain information about the optical field inside the PhC. The intensity and polarisation of this scattered light can be measured and the properties of the propagating light can be deduced. This technique can give a wide variety of information. In particular, the influence of the position of the propagating modes with respect to the folded air-light cone can be studied. We will present two examples. First, by studying the properties of the Fabry-Pérot-like mode scattered from a single line defect in a PhC waveguide, propagation losses were deduced from the attenuated diffracted light and compared to theoretical predictions. Second, by collecting the scattered light, a 'map' of the optical field inside a self-collimating structure was studied. The divergence of the beam was measured as a function of energy and compared to the results of equi-frequency analysis.

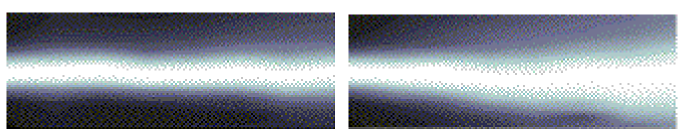

Fig. 1: Light scattered out-of-plane at different energies in a self-collimating PhC structure: (a) u=a/□=0.300 (self-collimated beam) and (b) u=a/□=0.303 (divergent beam)

All solid photonic band-gap fibres

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We report a simple all-solid photonic band-gap fibre [1]. The fibre (Fig. 1) was formed using two commercially-available silicate glasses. The transmission spectrum (Fig. 2) shows several low-attenuation windows, which stand out from the background by more than 30dB over just a few centimetres of fibre. The measured dispersion over two transmission bands has shown anomalous group-velocity dispersion in the transmission bands despite the large normal dispersion of the material. The bandgap formation in all-solid photonic band-gap fibres is attributed to anti-resonances of the high-index strands in the cladding.

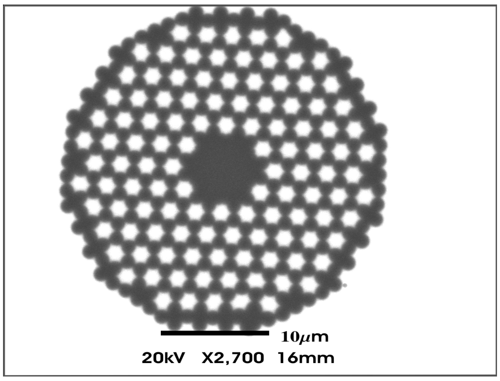

Fig.1 Back-scattered electron image of a fibre sample. The white area is high-index glass.

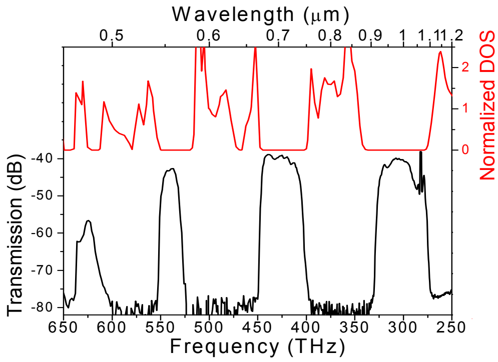

Fig.2 Measured transmission spectrum (lower curve) of a fibre sample (20cm long, 1.79μm pitch) and the computed normalized density of photonic states (above).

[1] F.Luan, A.K.George, T.D.Hedley, G.J.Pearce, D.M.Bird, J.C.Knight, and P.St.J.Russell, *OPTICS LETTERS,* 29, 2369 (2004)

Fabrication of 2D photonic crystals in chalcogenide glass membranes by focused ion beam milling

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We describe the production of chalcogenide glass photonic crystals in films of AMTIR-1 glass. Chalcogenides have sufficiently high refractive index (2.4-3.0) to create a photonic bandgap as well as a high third-order optical nonlinearity (100-1000x silica) and may be useful for all-optical switching [1-2].

300nm thick AMTIR-1 films were deposited by ultrafast pulsed laser deposition on 50nm thick SiNx windows prepared by anisotropic chemical etching of nitride coated silicon wafers. The crystal structures were fabricated using a focused ion beam (FIB) to mill away unwanted material from the SiNx side to create high quality lattices with periods of ≈500nm. Optical tests showed clear signs of Fano resonances in the angle dependence of the transmission spectra. This technique of fabricating photonic crystals allows arbitrary shapes to be made with <100 nm resolution.

[1] A. Zakery, Y. Ruan, A. V. Rode, M. Samoc, and B. Luther-Davies, *J. Opt. Soc. America B: Opt. Phys.*, **20**, 1844-1852 (2003).

[2] C. Grillet, D. J. Moss, D. Freeman, S. Madden, B. Luther-Davies, and B. J. Eggleton, submitted for *PECS-VI*, (2005).

FDTD analysis of nonlinear PBG waveguides for optical circuit applications

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Nonlinear PBG structures have attracted considerable attention as an optical material which is expected to play an important role in the future of the integrated optical circuits. In this study, a finite-difference time-domain (FDTD) method based on numerical simulation of oscillating dipole radiation [1] is used for Kerr-like nonlinear PBG waveguide analysis. In order to calculate dispersion characteristics of a PBG waveguide, the super-cell that includes an imperfect part of the periodic structure is used. A cubic equation is solved analytically within the main body of the FDTD algorithm to calculate the electric field intensity, which induces the nonlinearity [2].

A numerical tool based on the presented method can be used to analyze various components for integrated optical circuits. These components include PBG-based nonlinear directional couplers, all-optical switches, etc. Their functionality is explained through the analysis of dispersion characteristics and verified by conventional FDTD simulations. Some examples will be presented.

[1] I. S. Maksymov, L. F. Marsal and J. Pallarès, *Opt. Commun.*, (published online, 2005).

[2] I. S. Maksymov, L. F. Marsal and J. Pallarès, *Proceedings of the 12th International Workshop on Optical Waveguide Theory and Numerical Modeling,* Ghent, Belgium, 2004 (see also special issue OWTNM2004, to be published in Opt. Quant. Electron. in 2005).

Extraordinary optical transmission through finite arrays of holes.

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Extraordinary optical transmission (EOT) occurs in arrays of sub-wavelength apertures in metal films [1]. Theoretical studies have concentrated in the infinite array situation [2]. However, samples are always finite, and the problem of how large the system has to be in order to develop EOT has not been previously considered.

We present a formalism capable of analyzing the optical properties of even thousands of holes or dimples placed in arbitrary positions in a metal film. We show the evolution of EOT with number of holes (from 1 to infinite), and how EOT is already present in finite chains of holes [3], which can be considered as the basic entity showing EOT. Finally, near-field patterns of different structures are presented, and discuss their possible application to the field of plasmonic nanolithography.

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[2] L. Martín-Moreno et al. *Phys. Rev. Lett.* **86**, 1114-1117 (2001)
[3] J. Bravo-Abad, F.J. García-Vidal and L. Martín-Moreno. *Phys. Rev. Lett.* **93**, 227401, (2004).

Monomode mirrors for multimode photonic crystal waveguides

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Photonic crystals straight waveguides are easily multimode, so that designing cavities from closed waveguides yields poor results if no care is taken. Upon reflection at a mirror built up from deep trenches or "native" photonic crystal, the impinging fundamental mode partially feeds higher order modes, and the resulting eigenmode features increase losses and degrade quality factor.

A significant improvement results if the cavity is forced to operate on its fundamental mode by suppressing modal interactions at the mirror. We show here an appropriate design of the mirror shape for that purpose. In other words, the reflector shape is blazed in a way adapted to the discrete modes of the straight waveguide.

Cavity modes based on a "W3" waveguide have been calculated in 2D in a supercell, and analysed on the basis of the straight guide eigenmodes to quantify the modal reflection. We find a mirror shape preserving the symmetry of the fundamental mode and minimizing the projection on the higher order modes. Tenfold improvement is obtained at this stage. Finite-difference time-domain simulations are then used to evaluate all the optical properties of the proposed novel cavity structures.

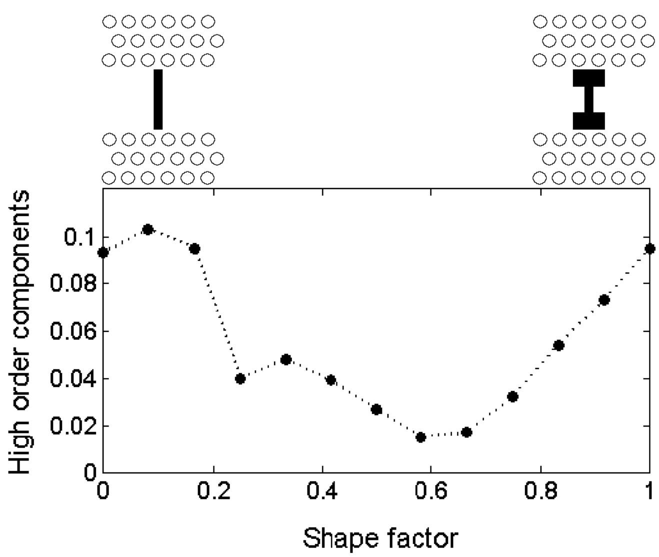

Fig.1 Evolution of higher order modes components of the reflection in a W3 waveguide as the shape of the mirror evolves from a simple trench to a blazed hole. The vertical dimensions are also optimized.

FDTD analysis of nonlinear PBG waveguides for optical circuit applications

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Nonlinear PBG structures have attracted considerable attention as an optical material which is expected to play an important role in the future of the integrated optical circuits. In this study, a finite-difference time-domain (FDTD) method based on numerical simulation of oscillating dipole radiation [1] is used for Kerr-like nonlinear PBG waveguide analysis. In order to calculate dispersion characteristics of a PBG waveguide, the super-cell that includes an imperfect part of the PBG structure is used. A cubic equation is solved analytically within the main body of the FDTD algorithm to calculate the electric field intensity, which induces the nonlinearity [2].

A numerical tool based on the presented method can be used to analyze various components for integrated optical circuits. These components include PBG-based nonlinear directional couplers, all-optical switches, etc. Their functionality is explained through the analysis of dispersion characteristics and verified by conventional FDTD simulations. Some examples will be presented.

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[2] I. S. Maksymov, L. F. Marsal and J. Pallarès, *Opt. Quant. Electronics*, (special issue OWTNM-2004, to be published in 2005).

An Optically Triggered Q-Switched Photonic Crystal Laser

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Significant design freedom enables photonic crystal (PC) cavities to be fabricated that support optical modes with specific, favorable characteristics. For example, PC cavities can be designed to possess modes that have electric field distributions with substantial overlap with the PC holes and cladding. Such structures are ideally suited for integrating fluidic nonlinear optical materials within intense optical fields generated by PC lasers. In creating our optically triggered Q-switched PC laser, we designed and fabricated a PC cavity optimized to support two orthogonally polarized lasing modes [1]. The cavity was infiltrated with nematic liquid crystal which could then be aligned optically using a layer of photoaddressable polymer. The birefringent liquid crystal determined the lasing mode's polarization and enabled tuning of the lasing modes. By rotating the liquid crystal, the relative cavity mode losses (Q) of each mode could be controlled and laser emission could be reversibly optically switched between the two cavity modes. Switching the laser emission between two cavity modes dramatically enhances the achievable tuning of the laser and may eventually yield PC laser tuning ranges that exceed 100 nm.

[1] B. Maune, *et. al.*, "An optically triggered Q-switched PC laser", in preparation.

Efficient second order counter-propagating parametric processes in centrosymetric materials.

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When a nonlinear Interaction is considered In the framework of a photonic crystal, the structuring of the material has proven to be highly relevant to reach a phase matched and an enhanced second order nonlinear interaction [1-3]. However, perhaps one of the most outstanding effects, but less explored, is the possibility to obtain a nonvanishing second order nonlinear interaction in centrosymmetric materials.

Experimental prove of the fabrication of a novel centrosymmetric material configuration for efficient 2nd order nonlinear processes is demonstrated. We show that several highly nonlinear organic molecules can be covalently bond onto the surfaces of specifically synthesized polystyrene microspheres, which allows the formation of a three-dimensional nonlinear photonic crystal. SHG measurements indicate that with such materials one obtains one of the highest conversion efficiencies for quadratic nonlinear process in centrosymmetric materials.

In addition, we a consider counter-propagating interaction in the framework of the same three-dimensional nonlinear photonic crystal, where perfectly phase matched interaction can be achieved, as a result of a nonlinear interaction at these interfaces. If one of these photonic materials with a sufficiently high nonlinearity is fabricated, one whould be able to observe the reflectorless backward parametric oscillation predicted by S. E. Harris thirty-nine years ago [4].

[1] J.Martorell, R.Vilaseca, and R.Corbalan, Appl.Phys.Lett 70, 702 (1997)
[2] M. Scalora, et al., Phys. Rev. A 56, 3166-3174 (1997)
[3] J.Trull, R.Vilaseca, and Jordi Martorell, J.Opt.Soc.Am.B 15, 2581 (1998)
[4] S. E: Harris, Appl. Phys. Lett. 9, 114 (1966).

Tailoring the properties of photonic crystals for light extraction in GaN

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GaN has become the prominent material for blue-green light emitting diodes (LEDs), but a significant challenge to the operation of these LEDs is the efficient extraction of light. Because of the index of refraction of GaN structures, about 90% of the light in current structures remains trapped in the material, primarily as guided modes. Our recent photonic crystal patterning of InGaN/GaN multiple quantum well material was designed to deliberately couple these guided modes into radiative modes by using a shallow, perturbative photonic crystal of 120 nm depth. Theoretical calculations predict that this approach could lead to extremely high extraction efficiencies with the appropriate photonic crystal geometry [1]. The earlier work utilized a triangular lattice photonic crystal with fixed parameters This work describes the more complete and systematic optimization of photonic crystal geometry, based on our theoretical predictions, to improve coupling and therefore increase the extraction efficiency. Characteristics of the photonic crystal including periodicity, fill factor, and hole depth as well as waveguiding properties of the structure have been varied in order to tailor the emission properties and extraction efficiency. Emission has been measured experimentally by angular-resolved photoluminescence and micro-luminescence.

[1] A. David et al., 'Photonic bands in two-dimensionally patterned multimode GaN waveguides for light extraction', submitted to Appl. Phys. Lett.

Coupling into the photonic crystal waveguides in the slow light regime

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Coupling of external light signals into photonic crystal waveguides becomes increasingly inefficient as the group velocity slows owing to an increasingly large mode impedance mismatch. We have systematically studied the efficiency of coupling from a strip waveguide into a photonic crystal waveguide for samples with different truncations of the photonic lattice at the coupling interface. Observation of fast oscillations near the transmission cutoff allows the spectral dependencies of the group index, coupling efficiency, and reflectivity at the coupling interface to be extracted independently. It is found that the coupling efficiency is significantly improved up to group indices of 100 for a truncation of the lattice that increases the local density of surface states, which are tuned in resonance with the slow light mode in the photonic crystal waveguide. Band structure calculations indicate that this resonant tunneling is responsible for increased coupling efficiency.

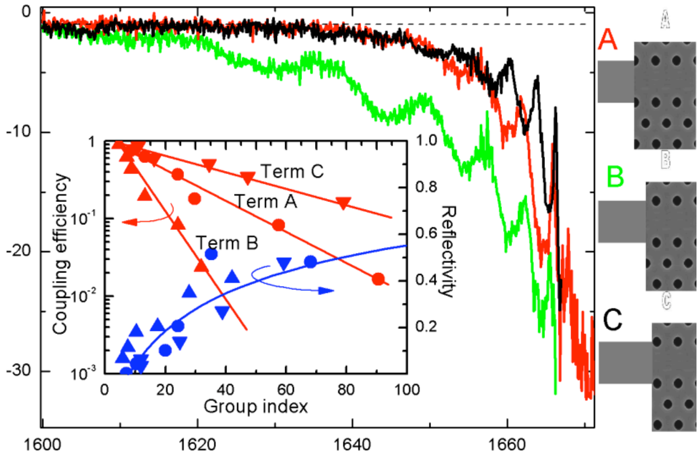

Fig.1 Transmission spectra of PhC waveguides with different termination of the coupling interface. Inset: coupling efficiency and reflectivity dependencies on the group index.

Resonant Modes in GaN photonic crystal defect cavities

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Photonic Crystal are of high interest for optoelectronic devices for numerous applications, e.g., as small volume resonators, on-chip waveguides, or for light extraction. These applications have successfully been demonstrated in other III/V material systems, such as InP or GaAs. However, there are only few reports on photonic crystals in the Nitrides. The reasons for this are, that the short emission wavelength of these materials in the visible range make the fabrication of significantly smaller features necessary to observe photonic effects, that GaN itself is more difficult to pattern, as it is chemically inert and does not feature a conventional wet etch.

We have developed a process based on electron-beam-lithography and reactive ion etching to produce photonic crystals with a lattice constant of a=200nm, by the use of a SiO_2 hard mask. We will also demonstrate, how these structures can be successfully underetched by means of photoelectrochemical etching (PEC), to form fully free-standing GaN membranes with active layers such as InGaN multi quantum-wells in the slab. Such membranes allow the confinement of the light in the vertical direction by the surrounding lower index material (air), and can be used in photonic crystal waveguides or cavities.

We will show results obtained on a H2 photonic crystal defect cavity in a triangular lattice. Low-Q modes are observed around wavelengths as short as λ=480nm, and the performance of the fabricated devices will be compared to FDTD simulations.

Planar Defects in Colloidal Crystals and their Prospective Applications

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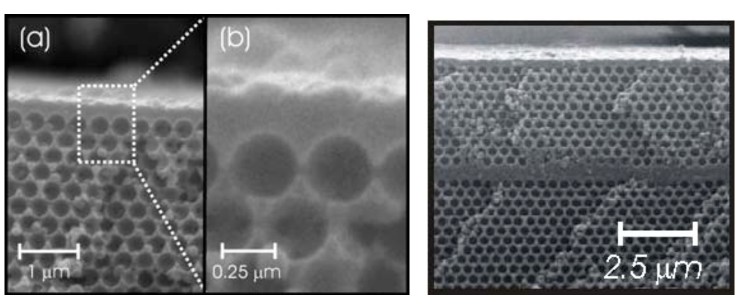
A combination of planarization, infiltration and coating techniques can be employed to create different types of planar defects in a colloidal photonic crystal. The effect of the presence of a dielectric slab of controlled thickness within the bulk of the material causes the appearance of allowed states at pseudogap frequencies, at which photon speed is slowed down.[1] Similar effects are observed when a dielectric slab is deposited on top of the crystal, the effect of surface resonant modes being observed in this case.[2] Different methods to attain these extrinsic structures from different types of materials, along with an experimental and theoretical description of the optical properties of both types of structures, will be presented.

Some recent attempts to make use of both intrinsic and extrinsic colloidal photonic crystal in optical sensor and photovoltaic prototypes will be described.[3] An enhancement of the different optical processes on which these devices rely on can be attained as a result of the presence of a colloidal crystal. Provided their processing technology could be extended to mass-scale fabrication, interesting prospective applications for these photonic crystals can be foreseen.



Scanning electron microscopy images of cross sections of planarizedinverse colloidal crystal thin films made of silica having a slabdeposited on top (left) and embedded within the bulk of the material(right).

[1] N. Tetreault et al. *Advanced Materials* **16**, 346 (2004).
[2] A. Mihi et al., *Physical Review B* **71**, 125131 (2005).
[3] N. Tetreault et al., *Advanced Materials, in press*.

Nonlinear Fano resonance in periodic photonic structures

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The Fano resonance is widely known across many diverse branches of physics as an asymmetric profile of transmission or absorption lines. One of the simplest models which may help to reveal the interference nature of this phenomenon is the discrete Fano-Anderson model. We generalize this model to the nonlinear case and characterize a shift of the position of the resonance and the bistable transmission. We show how this model can be directly used to describe resonant effects in a variety of photonic structures including two-dimensional photonic crystal (PC) waveguides. Especially, we show how long-range interaction in PC waveguides leads to interference phenomena in the transmission through waveguide bends, which could be associated with the Fano resonance. As the second example, we consider the resonant reflection of light in arrays of channel waveguides where tunable quadratic nonlinearity is introduced in nonlinear defects by periodic poling of single or several waveguides in the array. We demonstrate that the observed resonant scattering phenomenon can be characterized as the Fano resonance [1]. Recent successful experimental demonstration of quadratic waveguide arrays allows us to consider such structures as good candidates for the first observation of tunable Fano resonance in nonlinear optics.

[1] A.E Miroshnichenko, Yu.S. Kivshar, R.A. Vicencio, and M.I. Molina, Optics Letters (2005) in press.

Transmission enhancement for hetero-structure metal hole arrays

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The optical transmittance of the sub-wavelength holes can be enhanced by arranging them in a periodic array owing to the resonant excitation of the surface plasmon-polaritons (SPPs). In the THz region, however, the transmittance of the sub-wavelength metal hole array is very low compared with that in the visible region because of the extremely short attenuation length of the evanescent mode in the metal holes. In this paper, we investigated the transmission property of the hetero-structure metal hole array and found that the transmission is strongly enhanced.

Figure 1 shows the schematic diagram of the hetero-structure metal hole array (HS-MHA) used in our study. The metal layer with sub-wavelength holes (Layer2, diameter d_2=0.3 mm) was sandwiched by two other metal layers with the larger hole diameters (Layer1 and Layer3, $d_{1,3}$=0.8 mm). The spacing between the holes and the thicknesses are s=1.13 mm and t=0.25 mm, respectively, for all samples. The transmission spectrum of the Layer2 shown in Fig. 2 (dotted line) shows the very low transmittance because of the cutoff frequency of the metal hole at 0.59 THz. The transmission spectrum of the HS-MHA, on the other hand, shows the high transmission peaks at 0.48 THz and 0.28 THz (an enlarged figure is shown in the inset of Fig. 2), which correspond to the resonant frequencies of the second and first order SPPs. From the results of the finite difference time domain simulation, we concluded that such strong transmission enhancement for the sub-wavelength metal hole array is attributed to the enhancement of the electric field of the SPP which is excited strongly at the input surface of the outer layer (Layer1) of the HS-MHA.

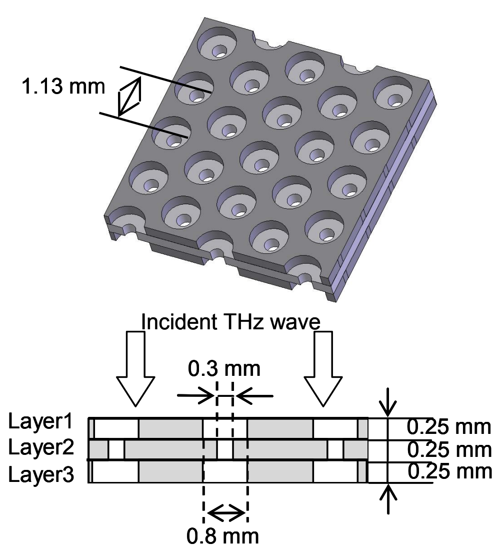

FIG. 1. Schematic diagram of the HS-MHA.

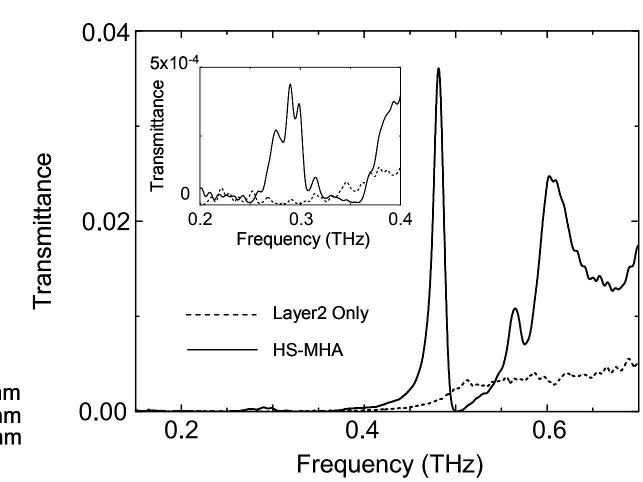

FIG. 2. Measured transmission spectra of Layer2 (doted line) and HS—MHA (solid line). Inset shows the enlarged figure at around 0.3 THz.

Fabrication of metal-clad plasmon resonators

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An infinite slit in a Drude material film shows resonance by multiple reflection of the propagation mode of a metal-clad waveguide[1]. As the slit width is reduced, the wavelength of the propagating wave becomes shorter; we can obtain a smaller optical resonator. We used a metal/dielectric/metal multilayer film to realize a very narrow slit. When a light polarized vertically to the substrate is incident from the side, the dielectric core layer works as a slit sandwiched between Drude materials. We manufactured resonators with various cavity lengths by milling Au/SiO_2/Au films with a focused ion beam. In the reflection spectra, dips predicted by the calculation[1] were observed. These are due to the plasmon resonance. As the cavity length becomes shorter, the dips moved from red to blue. Resonance of a plasmon with a wavelength as short as 100nm was observed in the visible frequency range.

[1] Y. Kurokawa and H. T. Miyazaki, PECS-VI, submitted (2005).

Theoretical analysis of Smith-Purcell radiation from 2D photonic crystal of dielectric spheres

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Based on the multiple multi-pole scattering theory, analysis is presented of light emission in the millimeter region when a high energy electron beam passes above a 2D photonic crystal made of dielectric spheres. Good agreement is achieved between calculated and experimental results. It is clarified that emitted light consists of the umklapp scattering process (Smith-Purcell radiation) as well as a direct excitation and propagation of photonic band states within the photonic crystal due to the existence of sample edge.

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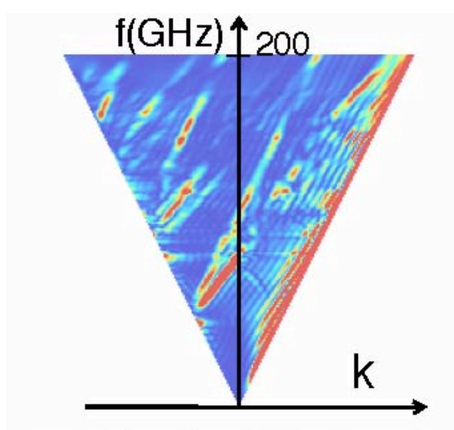

Fig. 1 Directional intensity distribution of emitted light within the light cone. Intensity increases from blue to red.

[1] K. Yamamoto et al., Phys. Rev. E**69**, 045601 (2004).

Chemical bonding of NLO chromophores to the sphere surfaces of a photonic colloidal crystal.

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Among other type of photonic crystal materials, organic based 3-D photonic crystals outstand because of their facility of processing, maneability, easy modulation via synthesis, and low cost (1). As it has been shown in the past, colloidal crystals, a particular kind of those organic photonic crystals can be used to enhance a second order nonlinear interaction (2). However, to enhance such effects it is necessary the surface modification with Non Linear Optical (NLO) chromophores of the polymeric microspheres that conform the colloidal crystal array.

Organic *push-pull* chromophores are good candidates to display large non-linear responses on such photonic crystals. We have synthesized a novel group of *push-pull* molecules derived from acridine and benzothiazole, to be incorporated to macromolecular systems, such as for instance over the surface of polymeric spheres of colloidal crystals. In addition, we have synthesized analogues of well-known highly nonlinear chromophores, like Ethyl Orange or Crystal Violet with a side linkable chain with the same purpose.

Immunology protocols of coating latex microspheres (3), based in the classical solid-phase methods of synthesis, were used to bind such molecules on a carboxylate-modified latex. In such conditions, coverage up to 60 % of the maximum possible was achieved. Measurements of SHG in such conditions resulted in a efficiency almost four orders of magnitude larger with respect to the case where the molecules were simply physically absorbed on the surface of the polymeric spheres of the colloidal crystal.

[1] See, for instance, C. Liguda, *et al. Appl. Phys. Lett.*, **78**, 2434 (2001). D. Pisignano *et al., Nanotechnology,* **15**, 766 (2004).

[2] J. Martorell, R. Vilaseca, and R. Corbalan, *Appl. Phys. Lett.,* **70**, 702 (1997).

[3] Among others, G. Quash *et al., J. Immun. Meth.*, **22**, 165 (1978). O. Siiman, A. Burshteyn, M. E. Insausti, *J. Colloid Interface Sci.*, **234**, 44 (2001).

Fabrication Techniques for active Photonic Crystal devices

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Hydrogen Silsesquioxane Masking for Photonic Crystal Fabrication.

The use of a spin-on glass (Hydrogen Silsesquioxane- HSQ) [1] as a mask for the etching of photonic crystals has a number of advantages relative to the more usual silica mask deposited using Plasma Enhanced Chemical Vapour Deposition. Not only is it a very cheap and versatile process with an etch resistance comparable to that of PEVCD silica, it is also less damaging to the electrical properties of the device. This is particularly important for active devices in which heating should be minimised [2].

Low Sidewall recombination In Quantum Dot Lasers

Due to the high confinement of carriers to quantum dots, carrier recombination at exposed surfaces is greatly reduced [3]. Thus, the active layer may be etched through with little loss in performance, allowing the advantages of high refractive index contrasts to be accessed. From lasers fabricated in Quantum Dot material grown by NL Nanosemiconductor GmbH, we measure threshold current densities for narrow devices that are more than an order of magnitude better than those from comparable quantum well devices. This makes Quantum Dots an ideal material for the realisation of active photonic crystal devices.

[1] H. Liou and J. Pretzer, *Thin Solid Films,* **335**, 186, (1998).
[2] M. V Kotlyar, L. O'Faolain, A. Krysa, and T. F. Krauss, *IEEE Photonics Technology Letters,* accepted for publication.
[3] D. Ouyang, N. N. Ledentsov, D. Bimberg, A. R. Kovsh, A. E. Zhukov, S. S. Mikhrin and V. M. Ustinov, *Semiconductor Science Technology*, **18**, L53, (2003).

Extraordinary optical transmission without plasmons

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Since the first demonstration of extraordinary optical transmission (EOT) through two-dimensional arrays of subwavelength holes in optically thick metallic films [1], this phenomenon has been studied in a variety of configurations. Namely, the models include the two-dimensional case (hole arrays of various shapes), and the one-dimensional situation (slit arrays). Realistic metals, perfect conductors, and other materials have been considered. It is widely admitted that the EOT is due to the coupling of the incident radiation to surface plasmon modes propagating on the metal interfaces, thanks to the surface corrugation. As a consequence, it is commonly believed that EOT is only possible for *p*-polarization because plasmons only occur for this polarization.

In this contribution we show that EOT is also possible for *s*-polarization. A surface mode is needed to mediate this resonant transmission. Since the plasmon mode is not available for *s*-polarization, we add a thin dielectric film on the metallic film. In this way, the system supports an electromagnetic surface wave and thus all EOT-phenomenology found for *p*-polarization can be reproduced for *s*-polarization, i.e., without plasmons.

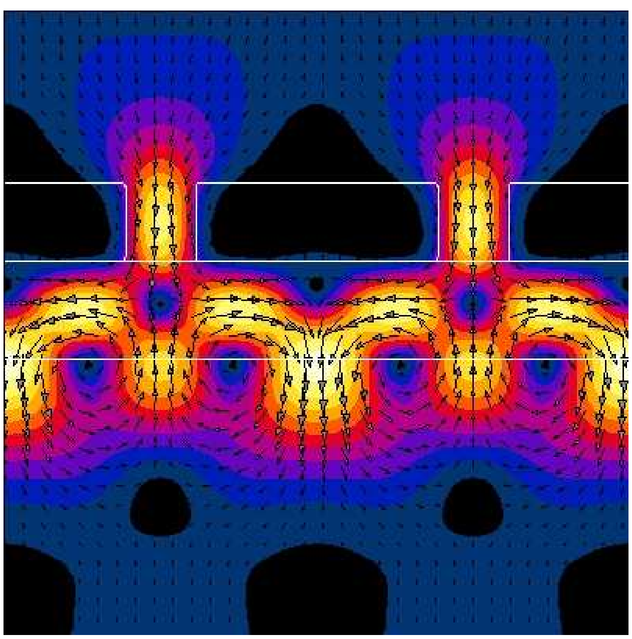

Fig. 1. Extraordinary optical transmission for the *s*-polarization case. A plane wave impinges (from above) on a structure made of a metallic film pierced by an array of slits, on top of a dielectric film. The plot shows the time-averaged Poynting vector field at the resonant frequency. The surface electromagnetic wave supported by the dielectric film mediates this resonant effect. In our simulations we have observed transmittances up to 100 % in perfect conductors and up to 80 % in realistic metals. Plasmons are not possible for this polarization.

[1] T. W. Ebbesen *et al.*, *Nature*, **391**, 667 (1998).

Improved Thermophotovoltaic Energy Conversion with 3-D Tungsten Photonic Crystal

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Recent advances in thermophotovoltaic (TPV) energy conversion efficiencies to greater than 20% has increased interest in investigating the use of TPV in a wider spectrum of applications. One of the issues associated with using TPV is the high hot-side temperatures (> 1000K) necessary to obtain conversion efficiencies greater than 20%. The elevated temperature limits the available materials that can be used as the hot-side emitter to either ceramics or refractory alloys which emit photons with a Planckian distribution. For semiconductor materials of interest for TPV energy conversion the ratio of convertible light to nonconvertible light is 25% for greybody emitters. Therefore, in order to increase the conversion efficiency, very complex cold-side front surface filter technology is utilized.

In order to relax the requirements imposed on the front surface filter, 3-D tungsten photonic crystals (PC) are being investigated for hot-side emitters in TPV energy conversion. The PC increases the emission in the convertible wavelength range (over bulk tungsten) and suppresses the emission in the non-convertible wavelength range, which results in a greater than 10% improvement in conversion efficiency. Recent efforts utilizing tungsten PC for mWe power conversion will be reported.

This work was supported by DARPA under the Radioisotope Micropower Sources (RIMS) program. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under Contract DE-AC04 - 94AL85000.

Disorder in metallic photonic crystals

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Recent advances in nanofabrication have demonstrated that the optical properties of metallic nanostructures can be tailored by periodic arrangement on top of a waveguide layer. In such systems, the particle plasmon can couple strongly to the waveguide mode, forming a so-called waveguide-particle-plasmon-polariton [1].

In this work, we investigate the influence of disorder on the linear optical properties of such nanosystems. We vary the positions of the nanostructures with respect to their original grid positions, controlling type and amount of the disorder precisely. Long-range and frozen-phonon disorder are characterized in detail by their two-point correlation function.

We find that the optical properties of the samples are strongly modified. Increasing disorder reduces the excitation efficiency of the waveguide mode, resulting in a reduced modulation depth of the resonance. Angle-resolved extinction measurements allow to determine the band structure of the samples. The different branches of the polariton show a decreasing band-splitting for increasing disorder due to a lowered spatial overlap of the wavefunctions of particle plasmon and waveguide mode. Different disorder models affect the linear optical properties in a characteristic way.

[1] A. Christ, S.G. Tikhodeev, N.A. Gippius, J. Kuhl, and H. Giessen, *Phys. Rev. Lett*. **91**, 183901 (2003)

SNOM for the optical characterization of photonic crystals structures

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The characterization methods by classical microscopy are not well adapted to the study of photonic crystals structures because of their lack of resolution due to diffraction. Scanning Near-field Optical Microscopy (SNOM) appears like a unique way of characterization since it allows a local mapping of the electromagnetic field of a component under working conditions, with a resolution less than the wavelength. These field maps make it possible to detect the defects and make a return on the technology and the design in order to optimise the devices.

In this work, we analyse the guided light within the basic building blocks of photonic crystals-based optical circuits on SOI, working in telecom wavelengths (1.3-1.6 µm). We will present results on various devices: a W1 guide, a 60°-bended W1 guide and a Y-junction. SNOM observations show the apparition of standing waves in the photonic crystals guides. Realizing a Fourier transform and applying a high pass filter to the optical image, we can highlight the presence of the Bloch wave propagating in the guides.

Purcell Enhanced and Inhibited Emission in 3D Photonic Crystals

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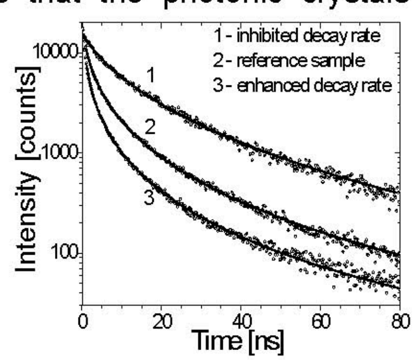
2) Debye Institute, Chemistry of Condensed Matter, Utrecht University, 3508 TA Utrecht, The Netherlands.

Control over spontaneous emission of light is essential to quantum optics and to diverse applications such as miniature lasers, LEDs, and single-photon sources for quantum information. We present experiments on emission from CdSe quantum dots (QDs) in 3D inverse opals. In time-resolved experiments, we observe that the photonic crystals control the emission decay rate of the QDs, demonstrating both broadband inhibition and enhancement [1]. For the first time we successfully interpret the emission dynamics of an *ensemble* of emitters (see Fig.): decay curves are modelled with a distribution of decay rates (curves). From this analysis we conclude that individual QDs experience even larger decay-rate modifications than the ensemble average.



[1] *Nature* **430**, 654 (2004); arxiv.org/physics/0410056.

Tailoring the spectra of Fabry -Pérot lasers using quasi-periodic grating structures

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J. Patchell, D. Jones and J. O'GormanEblana Photonics, Trinity College Enterprise Centre, Pearse Street, Dublin 2, Ireland

Conventional distributed feedback lasers can be regard ed as ID photonic crystal lasers where the translational symmetry and resultant photonic band structure determine the lasing modes of the cavity. More recently, lasing has been observed in the absence of external feedback in quasi-periodic photonic crystal structures, which offer new possibilities for spectral manipulation [1].

Here we present a transmission matrix calculation relating the threshold condition to the effective index seen by an optical mode in a Fabry-Pérot (F-P) laser. Our perturbative approach and the use of Fourier techniques allow us to solve the inverse problem relating the effective index along the cavity to the threshold gain modulation in wavenumber space. In this case the external cavity mirrors are the primary source of feedback while the construction of an appropriate quasi-periodic grating allows for the precise tailoring of the laser spectrum. As an application of the technique, single mode lasers at a predetermined wavelength near 1.5 micron are demonstrated.

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Light scattering by moving photonic crystals and dynamical Casimir effect

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We report on light scattering by photonic crystals moving with a constant velocity in the direction of its spatial periodicity. When a plane-wave is incident on the photonic crystal, its frequency and momentum components parallel to the boundary are shifted by the Umklapp scattering. In addition, it induces the radiation pressure as well as the acceleration or deceleration force acting on the photonic crystal. The work done for moving the photonic crystal against the deceleration force is shown to be the net flux of the induced radiation minus that of the incident radiation, provided that there is no absorption loss in the photonic crystal. This phenomenon can be regarded as a classical counterpart of the dynamical Casimir effect. The net flux generally increases with increasing velocity, so that high emission efficiency can be achieved with a relativistic motion of the photonic crystal. Moreover, the efficiency is strongly enhanced by the excitation of the photonic bands.

We will present these results and discuss their implication for the quantum friction and the dynamical Casimir effect[1].

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Efficient coupling to photonic crystal waveguides using surface plasmon waveguides

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We propose an efficient coupling method from optical fibres to photonic crystal waveguides via surface plasmon waveguides. It has been demonstrated that the field distribution of surface waveguides enables efficient coupling to optical fibres [1]. Furthermore, the high effective index of these waveguides [2]can offer an efficient way of coupling into photonic crystal waveguides. To couple surface plasmon waveguides to photonic crystal waveguides, we designed a structure which consists of athin gold layer (thickness~10nm) embedded in polymer on top of a photonic crystal waveguide and shows imulation results that indicate the viability of this approach.

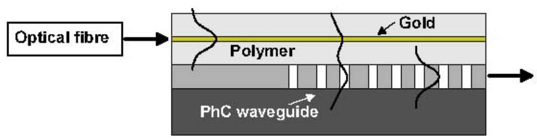

Figure 1 Surface plasmon waveguide on top of a photonic crystal waveguide.

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Ultra-low power nonlinear optics in photonic crystal mircroresonators

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The enhancement to the electromagnetic energy density provided by the large photon lifetimes and small mode volumes of photonic crystal (PC) microresonators reduces the input power required for the observation of nonlinear optical switching in these structures to micro-[1], and nano-watt levels [2]. For example, nominally weak semiconductor nonlinear processes, such as two photon absorption, free carrier absorption and dispersion, and Kerr self-phase modulation, play important roles in PC microresonators at sub-milliWatt power levels. Similarly, nonlinear processes in resonant cold atoms, whose third-order susceptibility can be 10^{10} times larger than that of typical semiconductors, are observable at single photon power levels when a single cold atom is located in a PC microresonator.

Here we report on the nonlinear response of a silicon PC microresonator. Taking advantage of an efficient fiber taper coupled PC waveguide input channel, optical bistability is observed for a dropped microresonator power of 100 uW, corresponding to 3 fJ of stored energy [1]. From these measurements a free carrier lifetime of only

0.5 ns in the highly porous PC is estimated. We also discuss the use of PCs in cold-atom cavity QED experiments, and address practical issues associated with integrating our fiber taper coupled devices with planar atom-chip waveguide systems in ultra-high vacuum environments.

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Bending and splitting of self-collimated beams in two-dimensional photonic crystal slabs

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Recently, the anomalous light propagation inside photonic crystals such as superprism [1], self-collimation [2], and negative refraction phenomena [3], has been intensively studied. In particular, there have been several works to realize an optical integrated circuit using self-collimated beams [4,5]. However, the lack of understanding on bending and splitting mechanism for self-collimated beams has rendered this optical integrated circuits unpractical yet.

In a recent study [6], we found theoretically that by using line defects bending and splitting of self-collimated beams can be efficiently controlled in ideal two-dimensional photonic crystals. For practical applications, however, systematic studies in two-dimensional photonic crystal slabs must be preceded. In this work, we present a computational study on the self-collimated propagation and the line defect derived beam bending and splitting phenomena in two-dimensional silicon based photonic crystal slabs supported by SiO_2 cladding. We first present an analysis of photonic band structures. Then we report simulation results obtained using the finite-difference time-domain method. Quantitative relation between the radius of defect holes and the power ratio of two split self-collimated beams is intensively discussed.

*Email: hypark@kaist.ac.kr

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Tunable Negative Refraction in Si-Polymer Photonic Crystal Membrane

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We report an extensive theoretical and experimental study on mechanically tunable photonic crystal (PC) membrane composed of Si rods and flexible polymer. The photonic band structure is extremely sensitive to structural changes and thus mechanical tuning provide much greater tunability than electro-optic methods [1]. Based on extensive simulations, we quantitatively defined relationship between the structural parameters and photonic bands. Wide tunability was predicted for both beam steering and sub-wavelength imaging. We fabricated test structures along with ridge waveguides with various incident angles for in-coupling (Fig. 1a). A 1.54 μm laser beam underwent negative refraction with an angle consistent with our simulations (Fig. 1b). To our knowledge, this is the first experimental observation of isotropic negative refraction in a Si-based planar PC structure at optical frequencies. We will present our latest results on various waveguide designs for unambiguous experimental demonstration of sub-wavelength imaging and the integration with MEMS actuators for mechanical tuning.

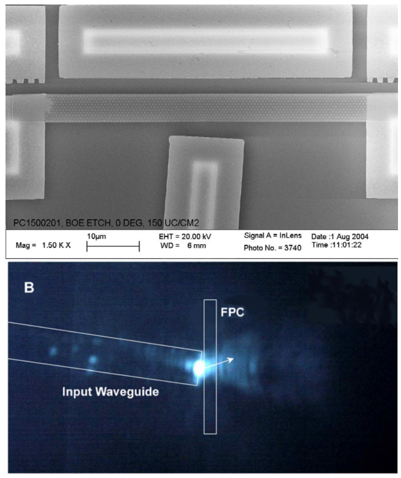

Fig.1 (a) SEM micrograph of the suspended Si-polymer PC membrane and the ridge waveguide for input coupling. (b) Experimental image of light scattered from a 6° angled input waveguide coupled into a Si-polymer PC region. The arrow indicates the direction of light propagation numerically obtained from the simulations.

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A Topological Phase Approach to Optimisation of 2D Photonic Crystal Geometries

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Singular optics, involving the study of topological phase, discontinuities, and defects has recently attracted much interest, e.g. [1]. Such concepts, where light propagation is controlled by geometric considerations, can also be applied to the study of photonic crystals (PC's), in particular to line-defect waveguides [2]. For example, it is well known that the design of an efficient 50/50 'Y'-coupler in a 2D PC is beset by problems such as back reflection, diffractive radiation, and unequal power splitting. Non-deterministic optimisation [3] of the 'Y'-coupler geometry has been successfully performed, but a clear theoretical understanding of the underlying mechanism for optimum light localisation is currently absent. It is the centre point of a 'Y'-coupler that represents a symmetry-breaking phase singularity (i.e. the location of a topological bifurcation) so making light behaviour less predictable. In order to maintain appropriate power and momentum conservation symmetries, couplers require a 'hidden' fourth arm, i.e. an 'X'-geometry, as is well-known in microwave technology with the "magic-T" device. Hence, the topological properties of PC geometries require careful design to exploit their full potential.

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Self-organized micro-structures of Tb3Sc2Al3O12/TbScO3 eutectic doped with Pr ions and their spectroscopic properties

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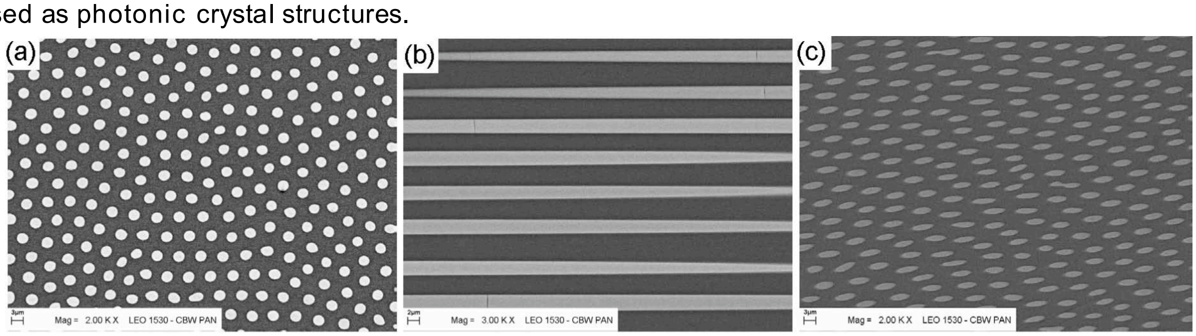
The self-organized dielectric micro-structures of two phases: Tb3Sc2Al3O12 and TbScO3 will be presented. Their growth is based on directional solidification of binary eutectics by the micro-pulling down method. The phases can be doped selectively for example with active elements such as lanthanide ions eg. Pr. Their spectroscopic properties will be presented. On Fig. 1 the eutectic microstructure is presented: (a) the cross-section, and (b), (c) the longitudinal sections. The properties of the material (such as lasing properties) together with the pseudo-periodic microstructure give the potential for these materials to be used as photonic crystal structures.



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Adaptive Curvilinear Coordinates in a Plane-Wave Solution of Maxwell's Equations in Photonic Crystal Fibre

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A method is described to compute the modes propagating at a given frequency in photonic crystal fibres (PCFs), using a plane-wave basis expressed in a system of generalised curvilinear coordinates. The coordinates are adapted to the structure under consideration by increasing the effective plane-wave cutoff in the vicinity of the interfaces between dielectrics, where the electromagnetic fields vary most rapidly. This amounts to representing the dielectric function and magnetic field on a real-space grid of the form of that in Fig. 1. In practice, calculations are performed in another space, where grids are uniform so that all advantages of plane-wave methods hold—in particular the use of FFTs [1].

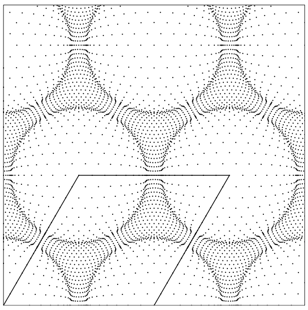

Fig. 1: Real-space sampling grid for a typical PCF cladding structure of air holes in glass.

We demonstrate the favourable efficiency and convergence properties of the method by comparison with the conventional plane-wave formulation of Maxwell's equations. Although the method is developed to study propagation in photonic crystal fibres, it is also applicable more generally to plane-wave modal solutions of structured dielectrics.

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Parametric dependence and optimization of left-handed materials

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May 19, 2005

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Abstract

We studied the transmission properties of one-dimensional meta-materials composed by split ring resonators (SRRs) and metallic wires. The attempt was to understand the behavior of this kind of meta-materials and to use this understanding to achieve large and broadband left-handed transmission.

For that reason we were performing a variety of simulations using different numerical approaches like the transfermatrix method (TMM), finite difference time domain (FDTD) and finite integration technique (FIT). We studied in detail the SRRs spectrum and recognized the various contributions in this spectrum. Moreover, we identified the parameters important for left-handed behavior and examined how the characteristic frequencies in the SRR and LHM spectra depend on various of the system parameters, like the rings size and gaps, the rings separation, thickness, orientation, dielectric board etc. Apart of the SRRs we also studied the behavior of a periodic system of wires, both infinite and finite, and the dependence of the meta-material transmission on the wires depth, width and position.

The results of the above mentioned study are (i) a physical picture of the operation of the SRRs and (ii) optimum parameters which are promising for large and broadband left-handed transmission.

Demultiplexing of acoustic waves in a two dimensional ultrasonic crystal

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We study the transfer of acoustic waves between two waveguides created in a phononic crystal. The two-dimensional crystal is a square lattice of steel rods in water, with a 3 mm period and a filling fraction of 0.55. Due to the strong contrast between acoustic impedances, this phononic crystal exhibits an absolute band gap from 250 to 325 kHz [1]. A full transmission band within the absolute band gap of the perfect crystal Is observed when a one period wide straight waveguide is created inside the phononic crystal [2]. Two such parallel waveguides can be coupled through a coupling structure exhibiting two perpendicular symmetry axes. The coupling element is constituted of isolated cavities interacting with stubs located at the sides of the waveguides. We observe that certain isolated frequencies are transferred from one waveguide to the other. We further study structures where the waveguide propagation band is due to the interaction between cavities [1]. More generally, we discuss the use of such devices for designing new acoustic or elastic waveguides, filters and demultiplexers.

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Small group velocity photonic crystal waveguides for group delay and dispersion management

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As was shown previously, there is a bandwidth of quasi-constant small group velocity in photonic crystal line defect waveguides sufficient for the single WDM channel operation [1]. In this paper, such waveguides are used as a basis for different time delay and dispersion control components with a size reduction proportional to the group velocity decrease. We consider an example of a waveguide with the group velocity 0.02 speed of light and the bandwidth of approximately 600GHz. The propagation through small group velocity waveguides of different lengths can have variable group delay without second order dispersion. The same waveguides with linearly chirped parameters [2] show constant second order dispersion in reflection with vanishing third order dispersion. The coupling of the small group velocity waveguide to a waveguide with normal group velocity gives more flexibility for the component design. The input and output channels can be separated in this case. The time delay and dispersion tuning is possible.

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Statistical Approach to Optical Characterization of 3D Layered Photonic Crystals

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Now it is well-known that periodicity of mesoscopic dielectric structures may create a situation when so called photonic prohibit zones appear. It is very attractive to use this effect for light transport controlling. However, today's technological difficulties usually give rise to some disturbance in a proper periodicity and monodispersity of 3D photonic crystals. Therefore there are many reasons to consider that practicable photonic crystal materials are not really an ideal periodical structure, but only a very high space ordered array of mesoscopic particles with some size distribution. The most effective theoretical approach for description of such media optical properties is the approach based on the statistical theory of multiple scattering of waves (STMSW).

Based on the STMSW, we have developed a numerical technique that allows to calculate coherent spectral transmission and reflection for three-dimensional (3D) layered photonic crystals consisted of monolayeres with a quasi-regular distribution of non-monodisperse dielectric spheres.

Multi-beam interference between monolayers was taken into account in the manner analogous to the transfer-matrix technique. Interference effects and electrodynamic coupling including near-field interaction between particles into a monolayer are considered in the quasicrystalline approximation as also was for 3D monodisperse layered photonic crystals [1,2]. Partial radial distribution functions for non-monodisperse close-packed monolayers were determined in the Percus-Yevick approximation from the solution of the generalized Ornstein-Zernike equation [3]. Single scattering properties are treated in the frame of the Mie theory.

We apply this technique to study the influence of particle size randomness on a bandgap spectral position and width, as well as on a short wavelength attenuation connected with incoherent scattering on particles of finite sizes.

The work is supported by the International Scientific and Technical Centre from Grant # B-276.

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Design and fabrication of Suzuki-phase photonic bandgap lattices and microcavities for the near Infrared

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We have studied and fabricated 2D Suzuki-phase lattices of holes in dielectric [1,2]. Plane wave expansion (PWE) calculations have been performed to obtain the photonic bands, showing for the TE mode a double photonic gap for normalized frequencies ω between 0.20 and 0.35 with two well-defined photonic bands inside it. These bands are very flat along the reciprocal lattice and it can be used to enhance the light interaction with the semiconductor material (InGaAsP) due to their low group-velocity for a wide range of k-vectors. We have also studied different cavities obtained by elimination of 1 or 2 holes, obtaining defect levels between the bands with localized modes. Finally, we have fabricated a Suzuki-phase lattice and measured its reflectivity spectrum between ω=0.20 and ω=0.35, obtaining well-pronounced Fano line shapes[3] for expected values.

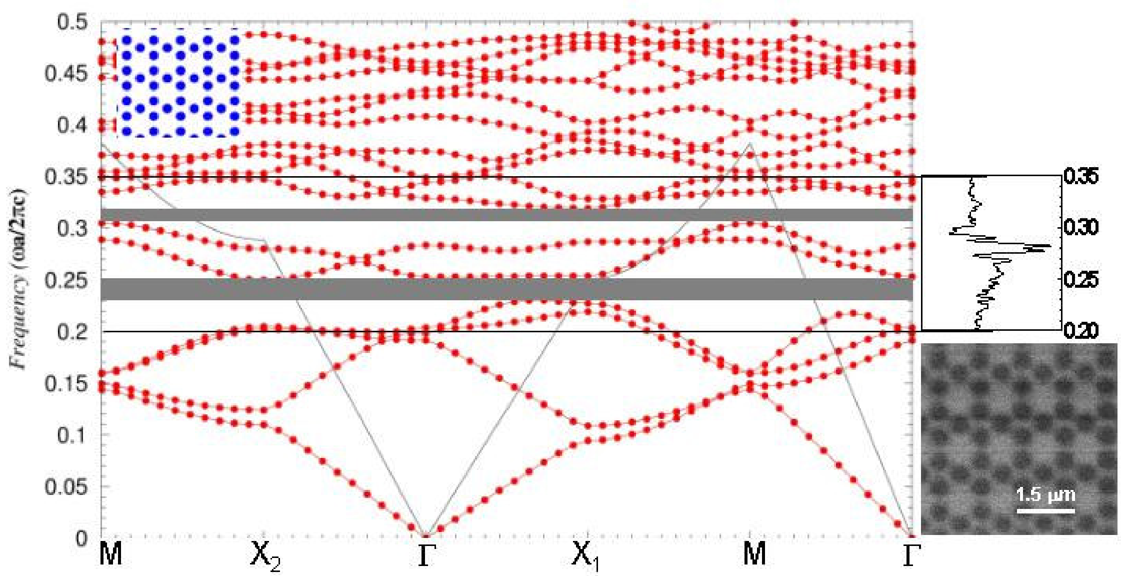

Fig.1. Photonic bands for the TE mode of the Suzuki phase lattice calculated by 2D PWE with an effective index of n=3.13. Inset shows the geometry of the lattice. Two gaps appear for normalized frequencies between 0.2 and 0.35 with two very flat bands between them. The SEM picture shows the fabricated structure with a=650 nm and r/a=0.33. Panel on the right shows the reflectivity FTIR spectrum at near normal indicence measured in the fabricated structure for normalized frequencies between 0.2 and 0.35.

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[3] U. Fano, Phys. Rev. **124**, 1866 (1961).

Beamsplitters based on air hole photonic crystals and ridge waveguides

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Beamsplitters for power or polarisation separation for photonic integrated circuits have been realised using air hole 2D photonic crystals in association with semiconductor ridge waveguides, in a compact configuration (less than 10 µm ×10 µm).

Efficiency of more than 99 % has been obtained for the power splitter from 3D FDTD simulations (fig. 1, inset), with the light being splitted in the two output branches, either equally, or unequally. Measurements carried out on structures realised on SOI (fig. 1) show efficiency around 80 %.

Polarisation splitters have also been realised in a similar configuration (with 3 rows of holes) and a 13 dB contrast, between TM and TE in one output branch, has been measured.

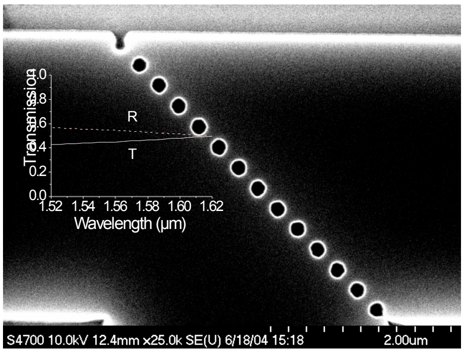

Fig. 1: Transmission spectrum (TM) in branches T and R (inset) and SEM picture of a photonic crystal power splitter, consisting of one row of holes, on a ridge waveguide T-junction

Two-photon polymerization of embedded features within self-assembled photonic crystals

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Three dimensional (3D) photonic bandgap materials have been proposed as the basis of many devices, the majority of which rely on the incorporation of aperiodic defects to provide functionality. We introduced and demonstrated the use of two-photon polymerization (TPP) for the fabrication of embedded features within self-assembled colloidal crystals.[1] This was the first identification of a technique capable of defining engineered 3D defects within this class of photonic crystals. We will discuss our unique modulated beam rastering approach to TPP and will introduce TPP phase diagrams that enable the visualization of the polymerization window.[2 We will present phase diagrams as a convenient means to evaluate the efficiency of different initiator systems as well as the impact of a colloidal crystal on the TPP response. Additionally, we will demonstrate the incorporation of high resolution optically interesting TPP features within silicon-air inverse opals and will present preliminary spectroscopy of these structures..

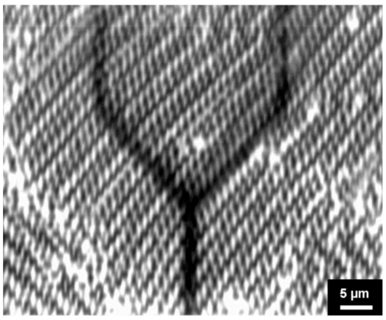

Figure 1. Fluorescence laser scanning confocal micrograph of a vertical cross-section through a TPP feature embedded within a self-assembled colloidal crystal. a self-assembled colloidal crystal

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Simultaneous optimization of mode dispersion, propagation loss, and guiding bandwidth in photonic crystal waveguides

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We demonstrate both theoretically and experimentally dispersion engineering in photonic crystal waveguides (PCWs) enabled by controlling the geometrical properties of the region next to the core of these waveguides. It is known that modifying the radius of the air holes next to the guiding region can be used to modify the frequency extent of the mode within the photonic bandgap (PBG) and to obtain single-mode guiding [1]. On the other hand, perturbing the periodicity of the two rows of the PCW next to the guiding region can be used to obtain linear dispersion and low guiding loss over a large bandwidth within the PBG [2].

In this paper, we demonstrate a systematic technique for dispersion engineering in PCWs by simultaneous modification of the hole size and periodicity next to the guiding region. We present theoretical and experimental results and show that this approach can be used to optimize PCWs for desired application. The results specifically show that it is possible to design practical single-mode PCWs with low loss over a large bandwidth. We also address the possibility of further controlling the dispersion properties of PCWs by modifying the index of refraction of the material inside the holes next to the guiding region.

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A compact low-loss photonic crystal demultiplexer based on the focusing superprism effect

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Superprism-based photonic crystal demultiplexers have recently received considerable attention due to their capabilities for realizing compact optical demultiplexers and spectrometers. However, it has been shown that in their conventional configuration, very large propagation lengths are required for high-resolution applications (e.g., in dense wavelength division multiplexing (DWDM) devices) [1]-[2] due to the diffraction of optical beams that correspond to different wavelength channels.

Here, we show that the source of limited resolution in these structures is the inherent diffraction effects on the optical beams propagating in the photonic crystal region. We show for the first time that by appropriate preconditioning of the beam, a focusing superprism effect can be realized, and devices made based on this concept can be an order of magnitude more compact compared to the conventional superprism-based devices. The key innovation in this proposed work is the combination of demultiplexing and focusing by carefully engineering the dispersion of photonic crystal. To the best of our knowledge, our result is the first actual demonstration of wavelength photonic crystal demultiplexers with practical length achievable using existing electron beam lithography and dry etching.

In addition to reducing the length of the device by at least one order of magnitude, we also introduce for the first time adiabatic matching stages [3] at the input and output interface of the photonic crystal demultiplexer to reduce the reflection losses considerably. The overall goal of this presentation is demonstration of an efficient, compact, and low-loss photonic crystal based demultiplexer.

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1D photonic crystals on ridge waveguides: a tunable Fabry-Perot cavity and a mode matched high quality factor microcavity.

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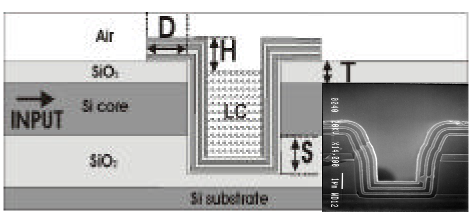
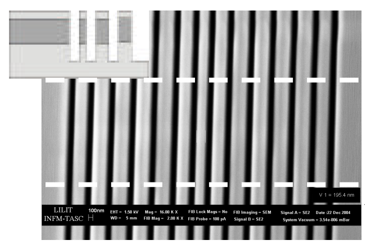
The integration of photonic crystals on waveguides has a very important role for future applications. The waveguide structure assures the confinement of the light along the transverse direction of the propagation, enabling a complete interaction of the propagating mode with the photonic structure. We show the experimental results and the theoretical analysis of two different devices composed by 1D photonic crystal on a monomodal ridge waveguide. The first device is realized on a SOI single mode ridge waveguide, where the photonic structure is composed by two symmetric DBR (SiO_2-Si stack layer), with a cavity between them, which is filled with liquid crystals. The tuning of the resonance peak transmission, around λ=1550nm, can be achieved applying an electric field between the two DBR. The second device has been realized on a Si_3N_4 single mode ridge waveguide where the photonic structure is formed by air slits removed from the waveguide. Varying the length of the first periods, the ones that face the waveguide and cavity, it is possible to decrease the insertion losses of the photonic device, thus increasing the quality factor of the cavity.



a)



b)

Figure1: a) schematic lateral view of the first device; the parameter S,T,D,H are adjusted to minimize the insertion losses of the device; the inset shows a SEM image of the realized device with the empty cavity. b) SEM image of the top view of the second device; the dashed white line shows the waveguide width. The inset shows a schema of the first three periods, highlighting the different period-length and filling fraction of the first one.

Some Approaches in Modeling Photonic Crystals and Photonic Crystal-based Structures

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Photonic crystals (PhC) or photonic bandgap structures (PBG) and photonic structures based on them represent nowadays very promissing structures of artifical origin, as opposed to „standard" structures in nature. They can indeed exhibit very specific properties and characteristics that can be very dificult (or even impossible) to realise by other means, mainly due to the existence of allowed and forbidden photonic frequency bands. Clearly, development and testing of numerical modelling tools on one side, and analysis and design of novel perspective PhC-based structures on the other side, are strongly interconnected. Hence, in the area of analysis and modelling, which is of interest in this contribution, several methods are currently being used, improved, implemented and applied for the numerical analysis of PhC structures worldwide. To study behavior and properties of photonic crystals, we have used several complementary methods: Plane Wave Expansion (PWE) method, the Finite-Difference Time-Domain (FDTD) method, and the Transfer Matrix Method (TMM). Concerning the PWE approach, we have used both our own software tool (PBS Solver) developed for calculating photonic band structures of two-dimensional dielectric photonic crystals (2D-PhC) and the well know free MPB code of more general computational capabilities. The PBS Solver (developed using the Matlab® environment) can be applied to compute PBS of very general classes of 2D-PhC structures (general definitions of lattices as well as basic building objects, including their combinations), with either analytic or numerical (using FFT) computational method for general and more complex structures, including one- and/or two-dimensional parametric dependencies calculations for optimization purposes. Concerning the FDTD approach, apart from using the freely available F2P code, our own FDTD Solver was implemented, to the moment with standard 2D Yee algorithms, and several types of boundary conditions applied: perfect electric conductor, periodic boundary condition, and perfectly matched layers. Concerning the TMM approach, we have relied on Translight code so far. Finally, several new interesting examples of results of PhC simulations (dispersion properties, transmission/reflection characteristics) will be shown, analyzed, and discussed. The various approaches will be also compared, showing the advantages and drawbacks of each method for different types of simulations.

Preserving Order in Highly Charged Colloidal Sediments: A Potential Route to Self-Assembled Photonic Crystal Templates

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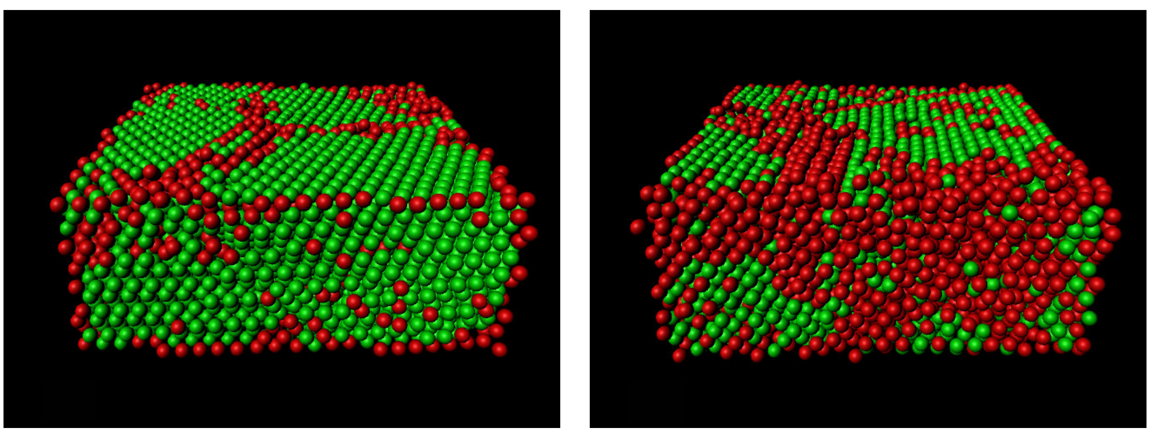
A three-dimensional real-space study is presented on the structural evolution of sedimented colloidal crystals upon gradual increases in ionic strength. Monodisperse SiO_2 spheres, 1 μm in diameter, are sedimented onto a glass coverslip in an index-matched solution of glycerol and water. Because of a negatively charged surface, the SiO_2 colloids have large inter-particle separations and constitute large, highly ordered crystalline domains. Upon the addition of 1 M NaCl, the negatively charged surfaces become screened out and the lattice contracts into adhesive surface-to-surface contacts. In this work, we present time resolved spatial data of colloidal sediments imaged with a laser scanning confocal microscope (LSCM) during NaCl addition. Our results show that the initial long-range crystalline order can be preserved when [NaCl] is slowly increased from 0 to 1 M. This suggests that charge-stabilized colloidal sediments with long-range order can be used to produce thick, large-area photonic crystal templates that are mechanically robust and unaffected by drying.



(a) initial (b) final

Fig. 1: These are 3-dimensional representations of an actual sedimented colloidal crystal. The sample was prepared by allowing 1 μm SiO_2 spheres to sediment onto a glass coverslip in an index matched solution of glycerol and water. The data was obtained using LCSM and the position of each colloid was plotted in perspective. The spheres are drawn to scale and color coded according to their local orientational order to highlight defect regions: green for perfect in plane hexagonal order, red for less than perfect order. Part (a) shows the colloidal crystal before NaCl was added. Part (b) shows the colloidal crystal 5 hours after 1M NaCl was added.

Genetic algorithms as a means to uncovering novel holographic photonic crystal structures

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Holographic lithography is an attractive technique for the fabrication of large-area, defect-free, three dimensional photonic crystals. Periodic structures were formed in the photoresist SU8, through concurrent exposure with 4 non-coplanar coherent beams of laser radiation (λ=351 nm). This generated a 3-D latent image within the photoresist which was developed using standard techniques, resulting in a 3-D microperiodic structure. Given the intensity, polarization, direction, and phase of each incident beam, it is straightforward to calculate the resultant intensity pattern. However, the inverse relationships between a given structure and the beam parameters are non-trivial and have not been fully established. We propose and will employ the use of genetic algorithms to solve for the beam parameters given an arbitrary structure. This approach may be interfaced with an iterative evaluation of the photonic bandgap properties in order to uncover interesting new structures which could be fabricated by multi-beam holography. Our genetic algorithm approach is a promising, versatile step towards the determination of the beam parameters required to fabricate novel holographic structures with potentially superior photonic bandgap properties.

Fractal interfaces in dielectric waveguides

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Ultimately the loss of a waveguide is dictated by irregularity or roughness along the guiding direction, if the constituent materials show negligible intrinsic loss and tunnelling or leakage loss is absent. The nature of the roughness, which is determined by the underlying physical processes that create it, has profound implications for the magnitude of the loss and how it scales with wavelength l. Typically the roughness contains significant spectral power at length scales comparable to and greater than l, so that the familiar $1/l^4$ dependence of Rayleigh scattering is not observed. Indeed, the roughness at the air / glass interfaces in Photonic Crystal Fibres has been found to be fractal over many decades of length scale that straddle l, resulting in a qualitative change in the wavelength scaling from the Rayleigh form. If the dimensions of the structure are considered as scaling with l, the fractal form implies a $1/l^3$ dependence of the interface roughness loss, but at a fixed structure size the dependence is more complicated. The paper will explore the wavelength dependence of roughness scattering loss due to fractal interface roughness for a variety of waveguide forms. In particular, it will be shown that a weak wavelength dependence typically results for waveguides which guide by total internal reflection.

Proximity-effects correction in photonic crystals with NanoPECS

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Integrated optical devices are often patterned using electron-beam lithography. In densely-packed structures such as, e.g., photonic crystals, proximity effects play in increasingly important role and degrade the pattern-transfer accuracy for acceleration voltages above 20kV. We have developed NanoPECS, an highly accurate tool for the correction of proximity effects. We have tested the suitability of various proximity functions. We have shown analytically that the double-gaussian function leads to unphysical ripples in the deposited energy of 2% peak-to-peak while the double-gaussian combined with an exponential term leads to much better pattern transfer in the resist with ripples of the order of 0.5%. Finally, we have applied NanoPECS to the correction of GaAs-based photonic crystals and shown that a hole-radius variation of 3.5% can be achieved compared to a 5% variation for a less accurate software.

Optically active photonic crystals by holographic lithography

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We demonstrate the use of chiral microstructure to make an optically active photonic crystal from material that is non-chiral in its bulk form. Face-centred cubic photonic crystals with a chiral basis are produced by holographic lithography.

Holographic lithography is a technique for the fabrication of 3D photonic crystals in which a 3D periodic interference pattern formed at the intersection of four laser beams is used to expose a thick layer of photoresist. Highly exposed photoresist is rendered insoluble while underexposed areas are washed away to reveal a polymeric photonic crystal with interconnected air voids. By controlling the polarizations of the interfering plane waves, which are used to define the 3D microstructure, it is possible to create left- and right-handed and closely-related non-chiral structures. The critical effect of structural chirality on the band structure of a photonic crystal is to produce non-degenerate circularly polarized bands. The result is optical activity that is produced entirely by the chiral microstructure created by holographic lithography. We anticipate that by combining the molecular-scale chirality of an infiltrating liquid crystal and a photonic crystal with engineered structural chirality it will be possible to achieve a high degree of flexibility in the design of polarization-sensitive photonic crystal devices

Scattered light spectroscopy of thin film opals and hetero-opals

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The added value of the scattered light spectroscopy of photonic crystals (PhCs) to the transmission one is that the former permits simultaneous examination of the photonic bandgap (PBG) along directions of the light incidence/detection and accounts for all existing optical modes of PhC. The range of demonstrated phenomena, like photon path memory, surface diffraction losses, hyperbolic functional form of the scattered light intensity diagrams, etc. comprises an independent toolbox for characterization of the regime of light scattering, PBG anisotropy, PBG dispersion and anomalous losses.
The magnitude and spatial distribution of light losses in three-dimensional well-ordered opal-based thin film PhCs with mainly ballistic regime of light propagation have been studied. Spectra and intensity angle diagrams of light scattered away from the beam propagation direction have been compared to that of transmitted light.
The scattered light spectroscopy has been applied to assess artificial two-dimensional defects in heterogeneous multiple-layer opal films. Comparison of spectra obtained in different configurations of scattered light collection in association with transmission spectra reveals that a defect becomes the major source of scattering of the traversing probe beam. Nevertheless, ballistic light propagation in hetero-opals dominates because low-angle scattered photons retain the optical path memory, whereas the large-angle scattering becomes diffuse. Due to the deeply embedded source the scattered light angular diagram appears strongly squeezed towards the hetero-opal film normal as compared to that of single opal film.
These and other experiments with scattered light will be presented to justify the advantages of the scattered light spectroscopy to study nearly-ordered PhCs.

Transition metal and rare-earth oxide inverse opals

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Recently, photonic crystal (PC) developments have also focused to find new applications in other research areas where photons influence physicochemical processes. Specifically, photonic crystals can be of application in areas where the control of the optical properties can improve processes in photochemistry. By combining structure, chemical reactivity and photonic properties one would expect high performances in different research fields like photoelectrochemical solar cells [1], photocatalysis, as well as sensors development. Therefore, it would be very promising to synthesize photocatalytic materials (as TiO_2, $Zr0_2$, etc.) with an appropriate PC topology. Our approach is the fabrication of inverse opals made of oxides of transition metal and rare earth, (i.e.: ZrO_2, Y_2O_3 and CeO_2 [2]) because they could provide interesting structural and functional properties for such applications.

Here we report on the fabrication method of inverse opals made of nanoparticles with especial interest in a carefully control of the optical properties. It is also very important to control the nanoparticle size and structure of catalytic materials that gives the best performances in photochemical processes.

[1] S. Nishimura *et a*l. J. Am. Chem. Soc., **125**, 6306, (2003)
[2] A. Corma et al. Nature Mater. **3**, 394, (2004).

Ring resonator add/drop filter based on a Photonic Crystal

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Common designs of ring-resonator add-drop filters use ridge waveguides, but the use of photonic crystals can lead to smaller devices due to their smaller bend loss. Such devices have been typically designed using micro-cavities with the proper characteristics [1]. Even though the possibility to realize cavities with whispering-gallery modes in photonic crystals is known and has been applied to the design of lasers, the use of this kind of cavities for add/drop filtering has not been explored. In this work, by using finite-differences time-domain calculations, it is shown that the realization of add/drop filters using ring-resonators is possible. When using a micro-cavity, it is necessary to couple to both modes because the functionality is obtained due to the superposition of the fields from both modes while in a whispering-gallery design. It Is desired to couple to just one of the modes, the one traveling In the proper direction. The required design considerations and the subsequent optimization of our device will be presented. Obviously, apart from add/drop filters, an improved ring resonator can also be useful in lasers.

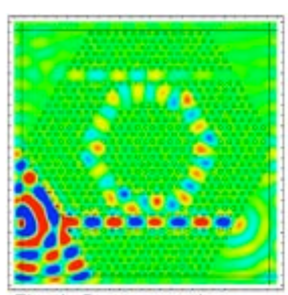

Fig. 1. Drop operation.
ε=11.56, Ω=0.3715, Q=430

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Tunable lithium niobate photonic crystals: Simulation -Fabrication Optical Characterization

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Lithium niobate is a very attractive material because of its many different physical properties (acousto-optical and electro-optical effects, piezoelectricity). We have already fabricated [1] and optically characterized lithium niobate photonic crystals showing the existance of a full photonic band gap (PBG).

In this work, we have chosen the electro-optical effect to realize a tunable photonic crystal device. In order to achieve the most sensitive photonic crystal configuration for the electro-optical effect in lithium niobate, we have performed numerical simulations based on the FDTD (finite difference time domain) method. The structure to be modelled is a 2-dimensional lattice of circular apertures, where different defect geometries have been studied.

In addition the fabrication and optical characterization of the previously simulated device will be presented.

[1] F. Lacour, N. Courjal, M.-P. Bernal, A. Sabac, C. Bainier and M. Spajer, **Optical Materials**, to appear (2005).

Complex interaction of polarized light with three-dimensional opal-based photonic crystals: Diffraction and transmission measurements

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We investigated the photonic bandgap structure of synthetic opals by combining optical polarization-resolved diffraction patterns and polarization-and angle-resolved transmission spectra. The diffraction patterns were observed as symmetrical sets of spots, each being a colored fingerprint of the photonic bandgap for a certain direction [1]. In transmission spectra, the measured energy positions of the deeps were found to be in a good agreement with the calculated data. We found strong anisotropy in intensity of both diffracted and transmitted light with different polarizations along special crystallographic directions. The polarization-resolved diffraction patterns and transmission spectra are discussed in terms of the two-band mixing formalism [2] for Bloch states in a photonic crystal taking into account the relative orientation of different crystallographic planes {hkl} in the opal structure. The conclusion has been made which bridges optical spectroscopy of photonic crystals and optical spectroscopy of conventional bulk homogeneous materials.

The support of the EC-funded projects PHOREMOST (FP6/2003/IST/2-511616) is gratefully acknowledged.

[1] A. V. Baryshev etal., Phys.Rev.B, **70,** 113104 (2004).
[2] D. A. Mazurenko etal., Phys.Rev.Lett.**91**,213903(2003).

Sub Wavelength Imaging Using Anisotropic Media

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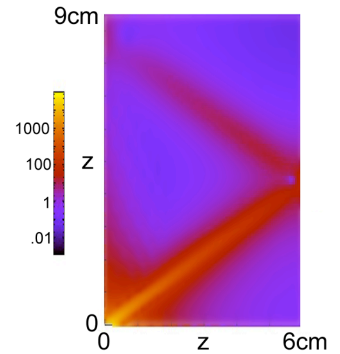
Waves propagate in anisotropic magnetic media according to the formula[1,2,3],

$$k_x^2/\mu_z + k_z^2/\mu_x = k_0^2 = \omega^2/c_0^2$$

As a result $k_x^2 >> k_0^2$ would normally imply that k_z is imaginary. Hence high resolution Fourier components of an image are normally confined to the vicinity of a surface. However if μ_x and μ_z have opposite signs both k_x and k_z can increase without limit and remain real. In such a medium fine details of an object can be transported, attenuated only by the losses encountered. In this paper we report an analytic solution for the propagation of waves across a slab of material and compare the analytical results to a full FDTD calculation and to experiment.



Intensity of the magnetic field, H_z^2, due to a point source at $x = z = 0$ showing reflection at the boundary of the medium located at $z = 6\text{cm}$. In this medium at 23.4MHz:

$$\mu_x = 1, \mu_z = -1.8 + 0.28i$$

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[2] K.G. Balmain, A.A.E. Luttgen, and P.C. Kremer, *IEEE Antennas Wireless Propag. Lett.* **1** 146 (2002).
[3] S. A. Ramakrishna and J.B. Pendry *Phys. Rev.* **B67** 201101 (2003).